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A determination of the spins of the 3.47 and 3.61 Mev levels in Zr^{90}

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With 3 figures in the text

ABSTRACT

The angular correlation of the 142 kev–1.14 Mev gamma cascade in Zr^{90} has been measured. The observed distribution function is $W(\theta) = 1 - (0.063 \pm 0.008) P_2(\cos\theta)$. A detailed discussion is given of the experimental results. It is shown that 5, 6, and 8 are the most probable spins of the 2.33 Mev, 3.47 Mev, and 3.61 Mev levels.

Introduction

This paper deals with a study by angular correlation methods of the spins of the 3470 and 3610 kev levels of Zr^{90} excited in the decay of Nb^{90}.

A detailed study of the decay of Nb^{90} was carried out by Mathur and Hyde [1] and Hok, Kramer, and Meijer [2]. An early angular correlation measurement showed, however, that the decay schemes proposed by the above mentioned groups could not be correct. This conclusion was also supported by the fact that the low energy levels of Zr^{90} proposed in the decay of Nb^{90} did not fit the well-known decay of Y^{90}. Later investigations by Lazar *et al.* [3] and Sheline [4] confirmed these conclusions.

Investigations made by Campbell, Peelle, Maienschein, and Stelson [5] showed that a sub-shell consisting of 40 protons might behave like a closed shell. Later Ford [6] predicted a level scheme for Zr^{90} with a first excited state with zero spin. Ford's predictions supported the existence of a 0+ state reported by Johnson, Johnson, and Langer [7]. Lazar *et al.*'s and Sheline's measurements gave further evidence that Ford's model was good. First excited levels with 0+ spin are characteristic for other closed shell nuclei, too (8).

The decay scheme of Nb^{90} proposed by Lazar *et al.* [3] and partly verified by Sheline [4] is shown in Fig. 1. Lazar *et al.* have arrived at this decay scheme after having done a large number of coincidence measurements which seem to support the proposal. Sheline has tried to measure the lifetime of the 2.33 Mev level after chemical separation of Zr^{90} from Nb^{90} in an ion exchange column. However, he did not observe any other half life than that corresponding to Nb^{90}. Sheline explains the negative result by proposing unusually long lifetimes of the oxidation states in the decay product.

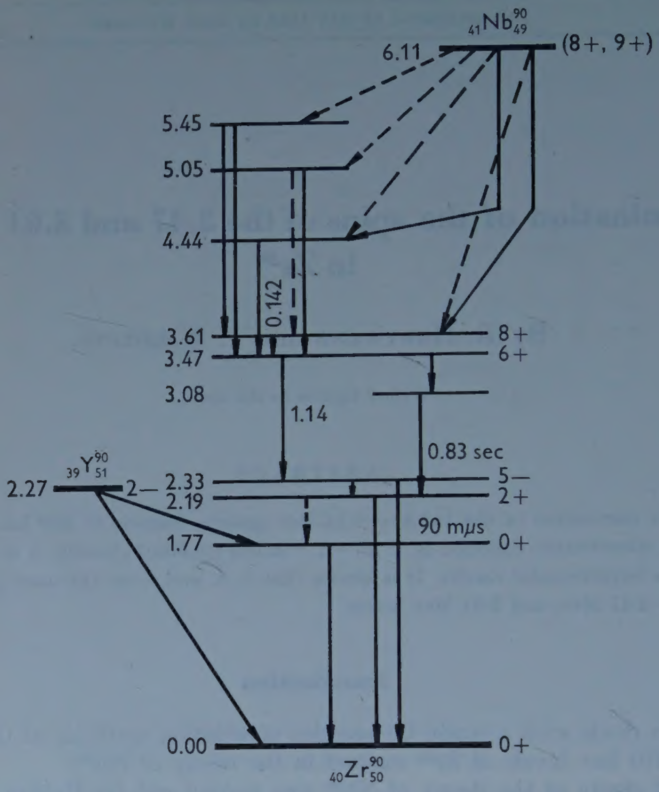

Fig. 1. Decay scheme of Nb^{90} (4, 5) and Y^{90} (8).

Statement of problem

The angular correlation measurement to be discussed in this paper is made on the 142 kev–1.14 Mev gamma cascade in Zr^{90} in order to get an idea of the position of this cascade in the level scheme and information about spins and multipole characters. The level scheme of Zr^{90} looks at first sight too complex to be suitable for angular correlation measurements when using scintillation spectrometers with their comparatively poor energy resolution. However, an analysis shows an accurate angular correlation measurement of the 142 kev–1.14 Mev cascade possible without much interference from other cascades. The 142 kev–1.14 Mev is the most intense prompt cascade in the decay scheme.

Source preparation

In the type of measurements reported here the purity of the source is extremely important. For this reason the sources were made in the following way. Mo^{90} which decays into Nb^{90} with a half-life of 5.7 hours was produced by the reaction Nb^{93} $(p, 4n)$ Mo^{90}. A stack of some few 0.1 mm thick niobium foils was irradiated for one hour at 80 Mev in the Uppsala proton synchrotron. The natural abundance of Nb^{93} is 100 percent. The chemical separation of molybdenum from niobium was started as soon as possible after the bombardment. The chemical procedure was the same as the one described by Mathur and Hyde [1]. Of course several other molybdenum isotopes can be obtained by (p, xn) reactions and these isotopes can cause errors in the correlation measurements. The following neutron deficient molybdenum isotopes can be obtained in proton bombardment of niobium: Mo^{90}, Mo^{91}, Mo^{92}, and Mo^{93} [9]. The existence of Mo^{89} is not known. Mo^{90} is the one of interest in this investigation. Mo^{91} has a half-life of 16 minutes and accordingly decays fast into Nb^{91m} of 64 days half-life and Nb^{91} (long-lived). Nb^{91m} emits only one gamma ray of 105 kev energy. The molybdenum isotope with mass number 92 is stable and the one with mass number 93 has an isomeric state (7 hours) apart from a very long-lived state (longer than 2 years). Mo^{93m} emits three gamma rays: 264 kev, 685 kev, and 1.48 Mev. Accordingly this isotope could cause some trouble but fortunately the gamma rays are in such an energy region that they can be discriminated. Finally Mo^{93} decays only by electron capture. As we have seen only Mo^{93m} could cause any interference effects but by using a very thin cyclotron target causing a very small energy absorption of the protons this isotope was probably efficiently discriminated against at the bombarding energy (80 Mev) used, since the yield curve of the reaction $Nb^{93}(p, n)$ Mo^{93m} has its maximum at about 11.5 Mev and drops fast above this energy [10].

The cascaded gamma rays of the excited states of Nb^{90} do not disturb the measurements since the life-time of the first excited level is long (24 seconds) [1].

Experimental

The apparatus has been described earlier [11]. In the present experiment the scintillation detectors consisted of sodium iodide crystals in connection with DuMont 6292 photomultipliers. The two crystals were of the following sizes: diameter 1.5 inches, length 0.5 inch and 1 inch respectively.

The niobium activity in the form of a powder was pressed into an aluminum cylinder 5 mm long and 1 mm in diameter. The wall thickness of the aluminium was 0.1 mm. Smearing out effects of the correlation due to source geometry are negligible. It is assumed that the lifetime of the 1.14 Mev transition is short enough not to have any influence on the angular correlation. In spite of Sheline's remark that the transition rate of this line is probably slowed down the life time is sufficiently short.

The gamma rays, the correlation of which should be measured, were differentially selected. The 142 kev line was selected in the channel with the small sodium iodide crystal and the 1.14 Mev line in the channel with the big crystal.

In considering whether coincidences may arise from gamma rays other than those selected, the 133 kev–2.2 Mev cascade is the most important case to be discussed, since the 133 kev line falls in the same window as the 142 kev line and is thus registered with practically the same counter efficiency as the latter line. The contribution from this cascade, however, is estimated to be less than 10^{-3}. The relative number of coincidences from the 1.84–0.142, 2.0–1.14, 1.6–1.14, and 1.0–1.14 Mev cascades is certainly small.

The correlation function was obtained from measurements at every 15° for counter angles ranging from 90° to 270°. The ratio of true coincidence rate to random rate was never less than ten. The maximum coincidence rate was about 55 counts per minute.

The corrections for the finite angular counter resolutions were calculated when the solid angles had been measured using the 113 kev energy in the decay of Lu^{177} and the 1.38 Mev line in the decay of Ho^{166}. These lines are each so close to 142 kev and 1.14 Mev that the corrections are obtained with acceptable accuracy.

Analysis of data

The data attained were fitted by a function of the form $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$. It was found that the function $W(\theta) = 1 - 0.063\ P_2(\cos\theta) + 0.00037\ P_4(\cos\theta)$ was the one best fitting the experimental data. As the coefficient of the last term is small it was regarded statistically correct to drop that term. Accordingly the angular correlation function is $W(\theta) = 1 - (0.063 \pm 0.008)P_2(\cos\theta)$.

Interpretation of the correlation function

An angular correlation measurement of the type described here is usually very difficult to interpret without a comparison with other types of measurements giving some kind of new information i.e. conversion coefficients or gamma ray intensities.

As it has earlier been proposed [1, 2] that the 142 kev and 1.14 Mev gammas are related to low-lying excited levels of Zr^{90} it would be interesting to see what the correlation measurement can tell us. It is then found that neither of the following spin sequences fits the correlation experiment (Zr^{90} is an even-even nucleus): 0–2–0, 1–2–0, 2–2–0, 4–2–0. The sequence 3–2–0 has $A_{2\,\mathrm{theory}} = -0.071$ which falls within the experimental accuracy but the conversion coefficient [3] of the 1.14 Mev line rules out a 2–0 spin transition. Accordingly, the correlation measurement eliminates the most common spins systematically found associated with low-lying excited levels in even-even nuclei and conversion coefficient measurements (Table 1) rule out the case which the correlation measurement leaves as possible and the results of these two types of measurements are supported by the fact that the first excited state found in the decay of Y^{90} has such a high energy as 1770 kev. It follows that the 142–1140 kev gamma rays cannot feed any zero spin excited level.

It is assumed in the following discussion that the decay scheme of Nb^{90} is the one shown in Fig. 1. Supposing a spin of 4 of the 2.33 Mev level and high spins of the 3.47 and 3.61 Mev levels, it is found that the correlation measurement fits only the sequence 7–6–4 which is ruled out for the same reason as 3–2–0. The sequence 8–6–4 has $A_2 = 0.102$ and $A_4 = 0.0091$ (the same values as 4–2–0). The cascade 6–5–4 and 7–5–4 give with $A_2^{\mathrm{exp}} = -0.063$ and $A_4^{\mathrm{exp}} = 0$ δ-values which do not satisfy simultaneously the two equations $A_2\ (\delta) = -0.063$ and $A_4\ (\delta) = 0$ where δ^2 is the intensity ratio of quadrupole to dipole radiation. It is thus concluded that the 0.83 sec metastable level does not have a spin of 4.

In cascades of the form $I_1 \rightarrow I \rightarrow 5$ the determination of the conversion coefficients (3) eliminates most I_1 and I values. The conversion coefficients of Table 1 fix the spin-differences to $|I_1 - I| \leqslant 2$ and $|I - 5| \leqslant 1$.

The cascade $2 \rightarrow 4 \rightarrow 5$ has the theoretical coefficients $A_2 = -0.071$ and $A_4 = 0$ and consequently it fits the experimental results quite well if both transitions are assumed to be unmixed. If the parity change is no in the first and yes in the second transition the conversion coefficients support these spins also. Then spin 2, however, is in contradiction to Ford's [6] spin and level suggestions.

Table 1. Experimental [3] and theoretical [12, 13] conversion coefficients of the 142 kev and 1.14 Mev gamma rays. The accuracy of Lazar *et al.*'s experimental conversion coefficients is not known but the errors are assumed not to be larger than ten percent.

	142 keV	1.14 MeV
	Theoretical	
α_1	0.0381	$2.16 \cdot 10^{-4}$
α_2	0.280	$4.89 \cdot 10^{-4}$
β_1	0.0755	$4.87 \cdot 10^{-4}$
β_2	0.560	$1.11 \cdot 10^{-3}$
	Experimental	
	0.297	$2.0 \cdot 10^{-4}$

Table 2.

	Spin sequence			
	$6\overset{\delta}{-}6$–5		$7\overset{\delta}{-}6$–5	
$\frac{M2}{E1}$	2.28	$3.6 \cdot 10^{-5}$	9	0.08
α	0.411	0.038	0.508	0.074
$\frac{E2}{M1}$	2.28	$3.6 \cdot 10^{-5}$	9	0.08
α	0.222	0.075	0.260	0.088

The cascade 5–6–5 is eliminated since the 1.27 Mev crossover is very weak. The spin sequences $6\overset{\delta}{-}6$–5 and $7\overset{\delta}{-}6$–5 give both δ^2 and conversion coefficients of the 142 kev line which do not agree with the experimental results. It is assumed that the 1.14 Mev line is a pure $E1$. Table 2 shows the conversion coefficients of the 142 kev line arrived at for the given spins and different δ^2 ($\delta^2 = M2/E1$ or $E2/M1$). In most cases they differ exceedingly from the experimental value 0.297 and consequently these two cascades are eliminated.

Finally, the cascade $8\overset{\delta_1}{-}6\overset{\delta_2}{-}5$ should be discussed. Since A_4^{exp} is small we can conclude that both the 142 kev and 1.14 Mev transtitions are probably not mixed to any appreciable extent as $A_4^{\text{theory}} = \frac{0.04343 + 0.4976\delta_1 + 0.08292\delta_1^2}{1+\delta_1^2} \cdot \frac{0.5360\delta_2^2}{1+\delta_2^2}$ is zero or small only for small δ-values if very large δ are neglected. This is reasonable since the conversion coefficients do allow only small admixtures if any. Another argument is that a mixture of two multipole characters in a 8–6 transition seems very improbable. Figs. 2 and 3 show A_2 and A_4 as functions of δ_1 and δ_2, Fig. 2 for

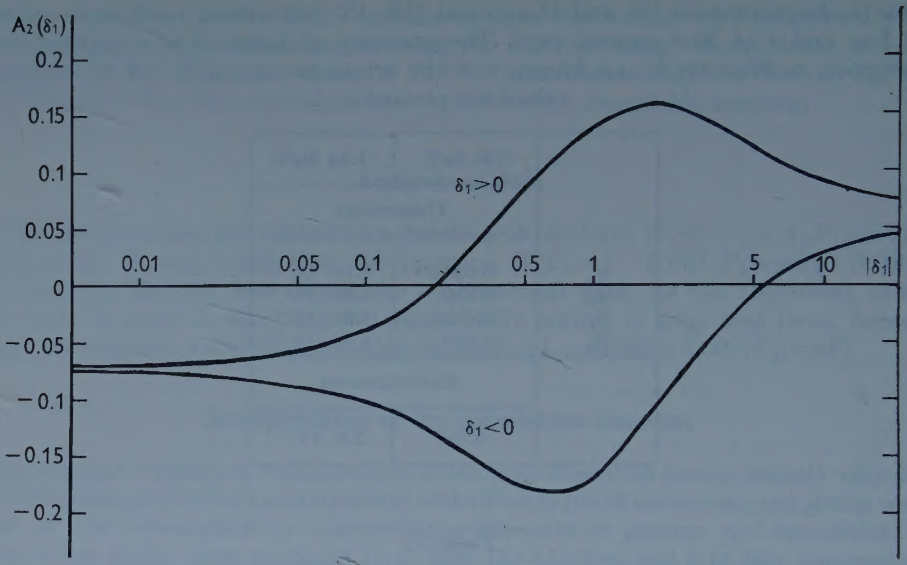

Fig. 2. A_2 as a function of δ_1 for the spin sequence 8–6–5, $\delta_2 = 0$.

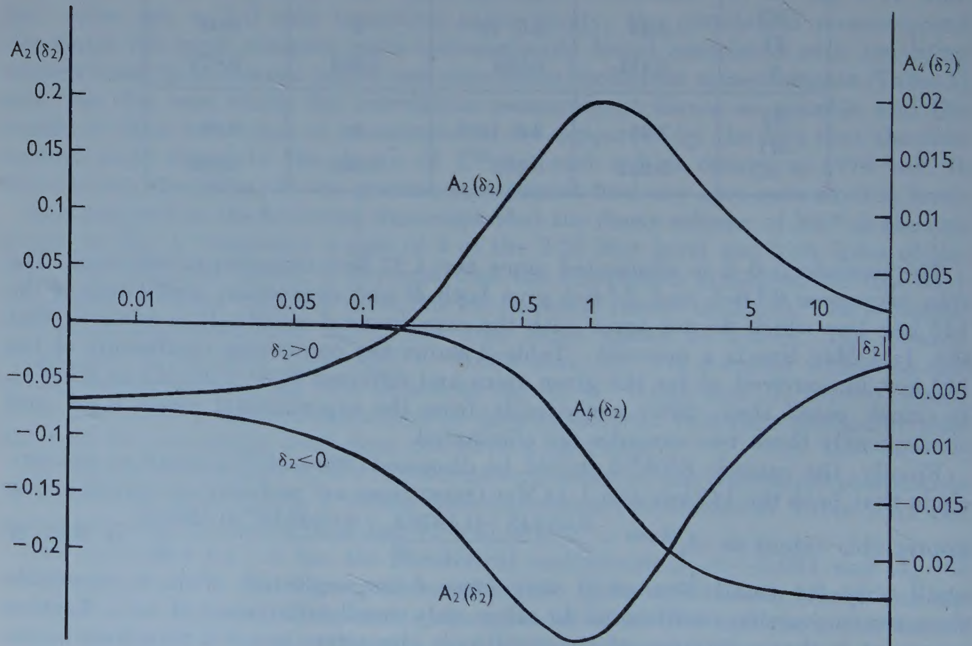

Fig. 3. A_2 and A_4 as functions of δ_2 for the spin sequence 8–6–5, $\delta_1 = 0$.

$\delta_2 = 0$ and Fig. 3 for $\delta_1 = 0$. The two figures show that the spin sequence 8–6–5 is consistent with the experimental results $A_2 = -0.063$, $A_4 = 0$ and also that neither the 142 kev nor the 1.14 Mev line is mixed, at least not to any appreciable extent. These spins are also in accordance with Ford's predictions.

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REFERENCES

1. H. B. Mathur and E. K. Hyde, Phys. Rev. *98*, 79 (1955).
2. O. P. Hok, P. Kramer, and G. Meijer, Physica *20*, 1200 (1954).
3. N. H. Lazar, G. D. O'Kelley, J. H. Hamilton, L. M. Langer, and W. G. Smith, Phys. Rev. *110*, 513 (1958).
4. R. K. Sheline, Physica, *23*, 923 (1957).
5. E. C. Campbell, R. W. Peelle, F. C. Maienschein, and P. H. Stelson, Bull. Am. Phys. Soc. *30*, No. 1, 33 (1955).
6. K. W. Ford, Phys. Rev. *98*, 1516 (1955).
7. O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. *98*, 1517 (1955).
8. I. Asplund and T. Wiedling, Arkiv för Fysik *15*, 303 (1959).
9. D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. *30*, 585 (1958).
10. G. E. Boyd and R. A. Charpie, Phys. Rev. *88*, 681 (1952).
11. T. Wiedling, Doctoral dissertation, University of Stockholm, 1956.
12. M. E. Rose, Internal Conversion Coefficients (North Holland Publishing Company, Amsterdam).
13. L. A. Sliv and I. M. Band, Coefficients of internal conversion of gamma radiation, Part I, *K*-shell (Report 57 ICC *K*1, Physics Department, University of Illinois, Urbana, Illinois).

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